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COMBUSTION DIAGNOSTICS OF PROPELLANT WITH NEW GRAIN GEOMETRIES

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MARCH 1988

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U.S. ARMY LABORATORY COMMAND

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High progressivity/density (HPD) propellants are under condiseration at the Ballistic Research Laboratory (BRL) for a variety of enhanced ballistic applications. The HPD concept involves the tailoring of the mass generation rate to match the increasing chamber volume as the projectile moves down the gun tube. This can be accomplished physically by designing a grain which will increase in surface area at a designated point in the ballistic cycle. It can also be done chemically by formulating grains with compositions that vary throughout the grain. As these layers burn through, the burn rate can be tailored to change at specific points in the ballistic cycle.

These propellants differ substantially from conventional gun propellants. Because of this, more extensive combustion diagnostics are required to be able to predict their performance in gun systems. We have conducted closed bomb and interrupted burner tests on

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selected HPD propellants. The data from the closed bomb studies has been reduced to derived burning rates and surface area profiles. Data from interrupted burner experiments complement deductions made from closed bomb firings. The studies demonstrate that controlled progressivity can be achieved in systems such as programmed splitting stick and faatcore propellants.

ACKNOWLEDGEMENTS

We wish to thank Mr. F.W. Robbins who both sponsored the programmed splitting stick propellant work and performed the closed bomb simulations. We also wish to acknowledge Mr. R. Fifer as he was the first to suggest the concept of fastcore to us. Sincere thanks go to the BRL closed bomb team, W.P. Aungst, J. Newberry, S. Lawing and J.O. Doali, for their unfailing experimental and data reduction support.

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TABLE OF CONTENTS

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LIST OF FIGURES

I. INTRODUCTION

Interior ballistic calculations are used by charge designers to predict gun performance and interior ballistic pressure-time and pressure-distance profiles. For many granular and stick propellant charges, predictions are reasonably straightforward and quite accurate, enabling rapid fielding of reliable new propelling charges. As performance requirements are increased, however, researchers are forced into charge design areas which seek to take advantage of new propellants and propelling charges having higher density and/or progressivity or improved chemical characteristics. Performance predictions for such charges are more difficult, however, since their burning characteristics can be significantly different from conventional propellants.

Ballistic predictions for charges made of conventional propellants require data on propellant burning rate vs. pressure, thermochemical, form function, and dimensional properties of the propellant grains. This information, along with other appropriate weapon and projectile input, is sufficient for the calculations. For nonconventional systems, however, additional data are required. Consolidated, deterred, layered, unslotted and programmed splitting stick propellants (concept to be discussed later) each pose unique informational requirements over and above the input data mentioned above. For consolidated propellants, data are needed on both the deconsolidation of the charge and the form function behavior of the deconsolidated grains. In the case of deterred propellants, the depth and concentration of the deterrent profile are needed along with the burning rate versus pressure behavior of the various parts of the deterred layer. For unslotted stick propellants, information is needed on erosive burning and/or grain fracturing effects. Finally, in the case of layered and programmed splitting stick propellants, information is needed on the physical integrity of the propellant sample and its burning behavior as a function of the distance burned into the grain. The added complexity in the burning of such propellants places additional burdens on the experimental diagnostics of their combustion properties.

While the pressure dependence of burning rate can be reliably obtained for any standard propellant from conventional closed bomb tests,[1] ancillary methods such as interrupted burning, flash x-ray diagnostics, high speed cinematography, and thrust tests are sometimes needed to study the burning properties of nonstandard systems. Even when standard closed bomb tests are applied to unusual propellant systems, it is frequently necessary to reduce the data in unusual ways. A good example of such reduction methods is the surface area profiling, or "inverse" closed bomb analysis technique.[2] At other times, when it is likely that the underlying assumptions in our normal burning rate analysis have been violated, we may still find it useful to speak of "apparent burning rates" in order to compare the burning behavior of related propellant samples under essentially the same conditions.[3] In the past we have successfully applied a number of these techniques in studies of nitramine,[4] consolidated,[5] perforated stick,[6] and very high burning rate[7] propellant systems.

In the present study, our task was to examine the combustion behavior of two unusual propellant systems, programmed splitting stick[8] and "fastcore".[9] The programmed splitting stick propellant concept is illustrated in Figure 1.

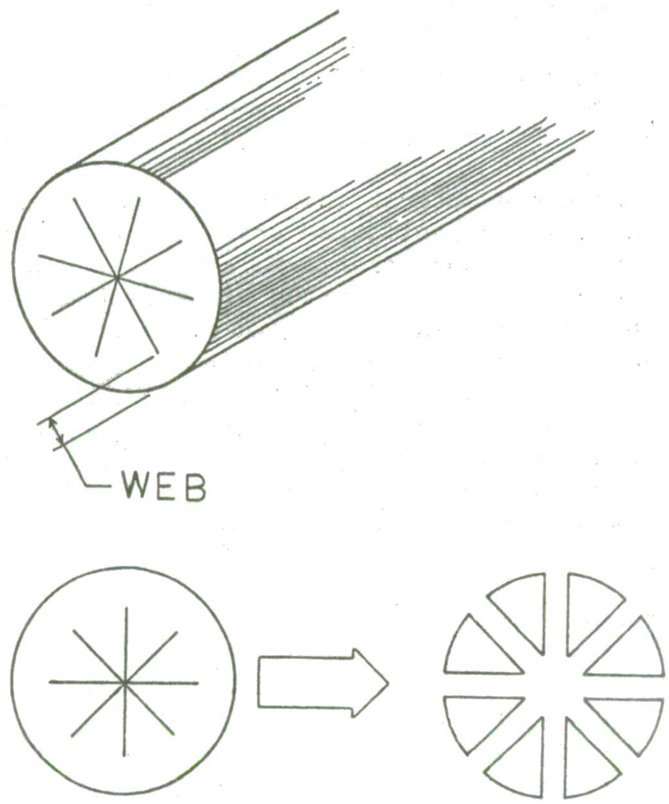

Figure 1. The Programmed Splitting Stick Propellant Concept

In this case, the propellant, NOSOL 363, is extruded in a cylindrical shape with star-shaped slots in the interior. The ends of the grain are sealed. On burnthrough of the outer web, the propellant breaks into a number of slivers, resulting in a large increase of surface area. This large surface area increase can have significant ballistic advantages.[10] The down-bore pressure can be tailored to obtain increased velocity for a given charge weight. The "fastcore" grain is illustrated in Figure 2. In this case an increase in mass generation rate is sought through the change in the burning rate properties of the propellant on going from the "cool" outer layer, NOSOL 318, to the more energetic, "hot" inner layer, NOSOL 363. This increasing gas generation rate is designed to occur when the projectile is down bore to increase muzzle velocity.

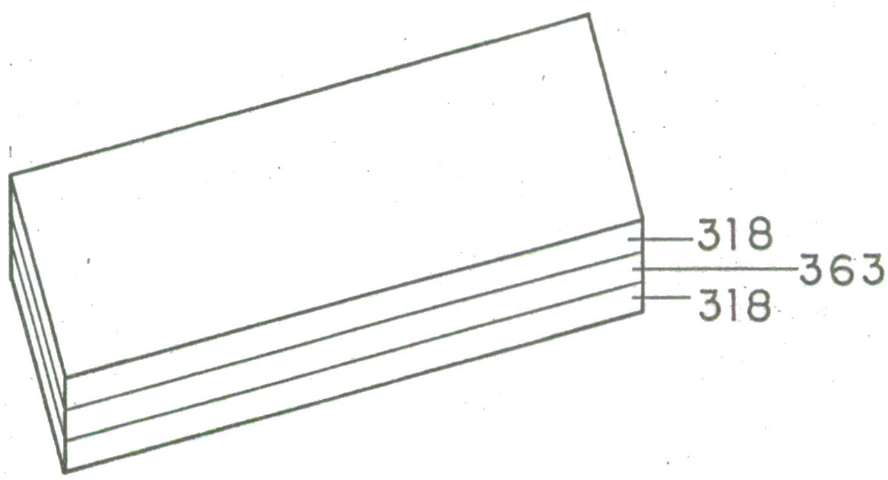

Figure 2. <u>The Fastcore Propellant Concept</u>

The studies to be described demonstrate the advantages of combining experimental and/or unusual data reduction techniques in studying the burning of novel propellants. In the present case, closed bomb and interrupted burner studies as well as "inverse" reductions of the closed bomb data were used to help piece together a picture of the combustion details of the samples.

II. EXPERIMENTAL

1. INTERRUPTED BURNER TESTS:

The interrupted burner, pictured in Figure 3, was used to screen samples prior to closed bomb firing and to complement the closed chamber firings. One chamber had a volume of 66 cm^3, and a diameter of 22.9 mm. A second chamber had a diameter of 37 mm and a volume of 156 cm^3. The burst discs were designed to rupture at pressures from 7 to 60 MPa. From one to three grains were used depending on the distance to be burned into the web. The grains were weighed before firing and all the recovered fragments were weighed after firing. The grain recovery device consisted of a wire basket lined with a soft, water-soaked sponge. The grains exiting the chamber frequently had a velocity such that the grain residue was embedded in the sponge. There was no evidence that much fracturing was caused by this process. The grains were ignited by an ignition system consisting of a M-100 match and one gram of Class 6 black powder contained within a thin tissue bag. The propellant grains were attached to the igniter with a 0.25 mm diameter wire to insure that no inhibition of surface burning would be caused by tape or glue.

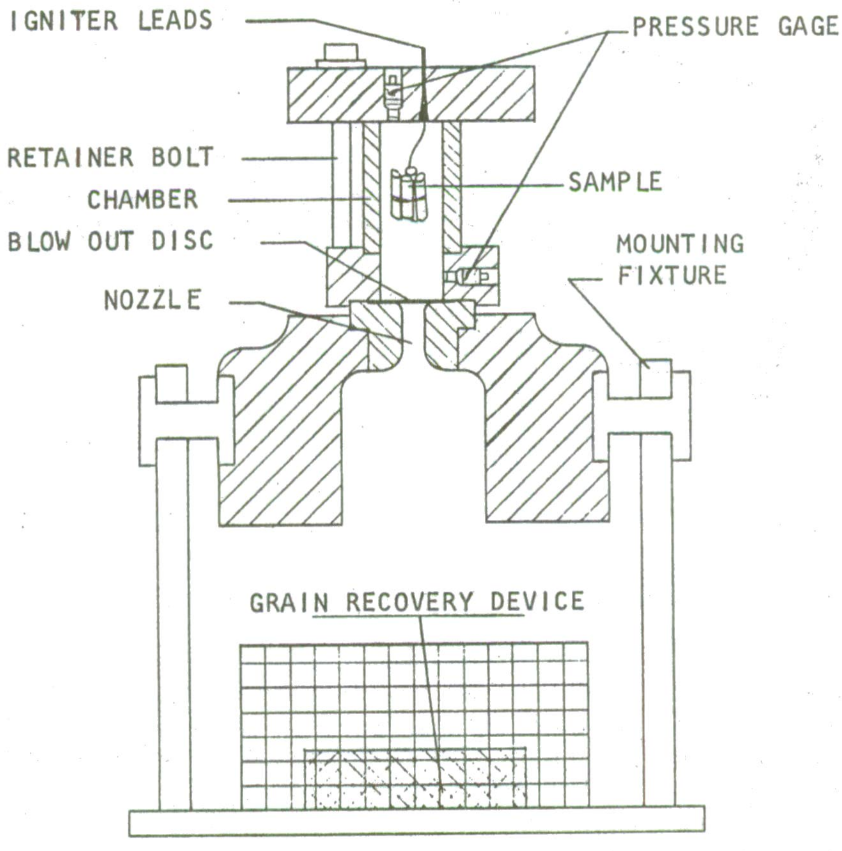

Figure 3. Schematic of Interrupted Burner

2. CLOSED BOMB TESTS:

Closed chamber tests were performed in the 850 MPa test fixture pictured in Figure 4. The vessel was manufactured by Harwood Engineering Company. The chamber cavity is 109 mm long and 50.8 mm in diameter with a hemispherical rear inner surface. The volume is 210 cm^3. Pressure measurements were made with a Kistler 607C-4 transducer and a Kistler 504E charge amplifier. Data was acquired on a Nicolet Explorer III digital oscilloscope, followed by data reduction on a PDP 11/34 computer using the CBRED2 code.[2]

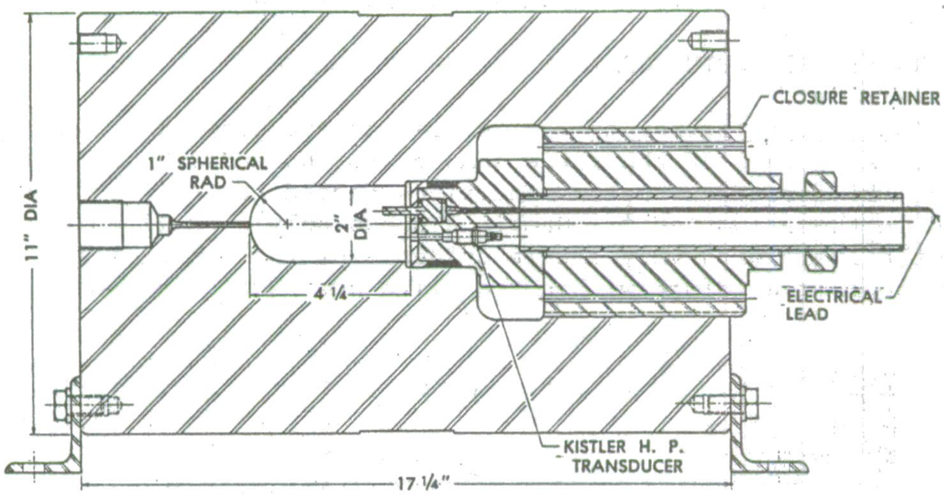

Figure 4. High Pressure Vessel used for Closed Bomb Testing.

All samples were ignited using an Atlas M-100 electric match with 1-2 grams of Class 6 black powder attached to it. The samples were prepared by bagging the propellant in cellophane and inserting the ignition squib into the bag before closure. All samples were fired at ambient temperature at a loading density of 0.25 g/cm^3.

3. PROPELLANTS:

The programmed splitting propellant (Figure 1) was made by the Naval Ordnance Station at Indian Head, Maryland by extruding NOSOL 363 (Lot RAD-1-2-73). The grain size of the propellant varied a little from lot to lot but nominal dimensions were 7.3 mm in diameter and 64 mm long with a "web" of 0.94 mm. This grain geometry required the development of end sealing techniques to prevent premature flame intrusion into the perforation. Several methods were tried, with varying amounts of success. Sealing agents that were experimented with included asphaltum, acetone, collodion, epoxy, Duco cement, and estane 5712. All of these agents were used alone and the epoxy was also used in conjunction with aluminum end caps.

The fastcore samples (Figure 2) were composed of NOSOL 363 and NOSOL 318 with the middle layer of NOSOL 363 sandwiched between two outer layers of NOSOL 318. These samples were also prepared by the Naval Ordnance Station at Indian Head, Maryland. The samples were delivered as sheet stock. Nominal grain dimensions were 50 mm long, 38 mm wide, and 6 mm thick.

III. RESULTS AND DISCUSSION

1. PROGRAMMED SPLITTING GRAINS:

a. Interrupted burner tests. A view of the propellant is shown in Figure 1. A picture of the three samples (4, 6a and 6b) is shown in Figure 5. Different extrusion conditions caused the differences observed in these samples.[10] Sample 4 shows only a small hole down the axis of the grain with very little evidence of the radial slits. Sample 6a shows some free volume within the slits and sample 6b shows none.

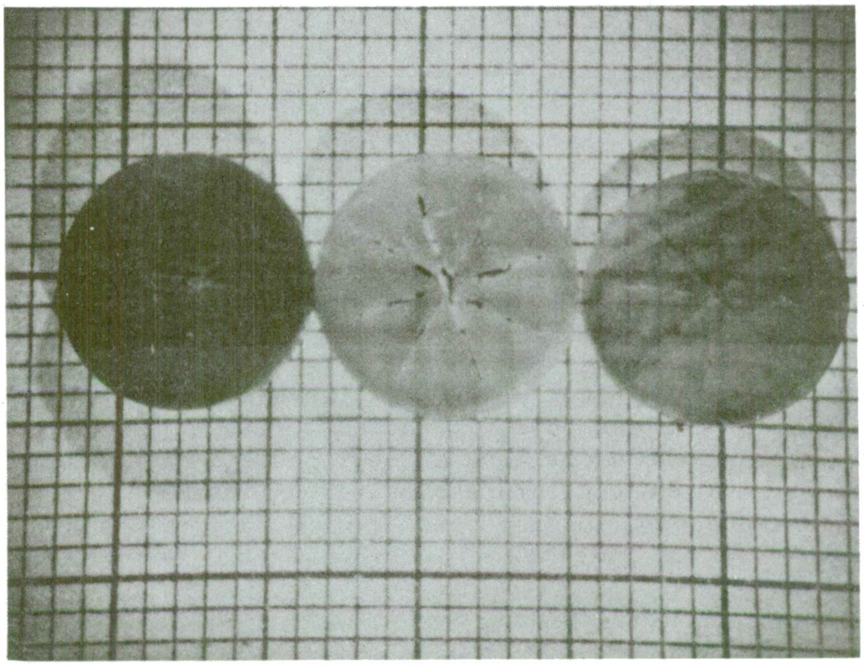

Figure 5. End View of Programmed Splitting Grains; Sample 4, 6a, and 6b.

Sample 4 was burned without any seals on the ends of the grain and the results are seen in Figure 6. It is clear that very little "memory" of the slits remains because the propellant burned as though it was a single perforation grain.

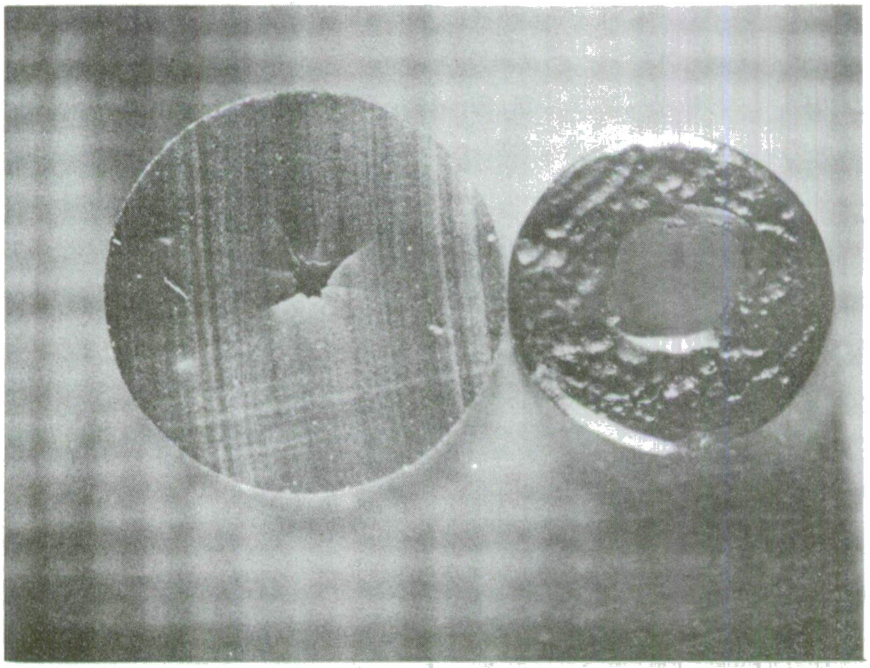

Figure 6. Sample 4; Unburned, Burned.

Figures 7 (end view) and 8 (side view) show the residue from sample 6b. It is clear that the grain has burned down through the slits but, nevertheless, the grain has remained intact. It is proposed that the slits re-seal as the thermal wave moves radially into the grain. The pressure time history was very smooth as would be the case for cord-like combustion. These tests were repeated in the larger volume combustion chamber (156 cm^3) with more than one grain and the results were essentially the same. Burn times to blow-out pressures were approximately 50 ms, similar to that in the closed chamber experiments but pressures where splitting occurred were lower (15 MPa).

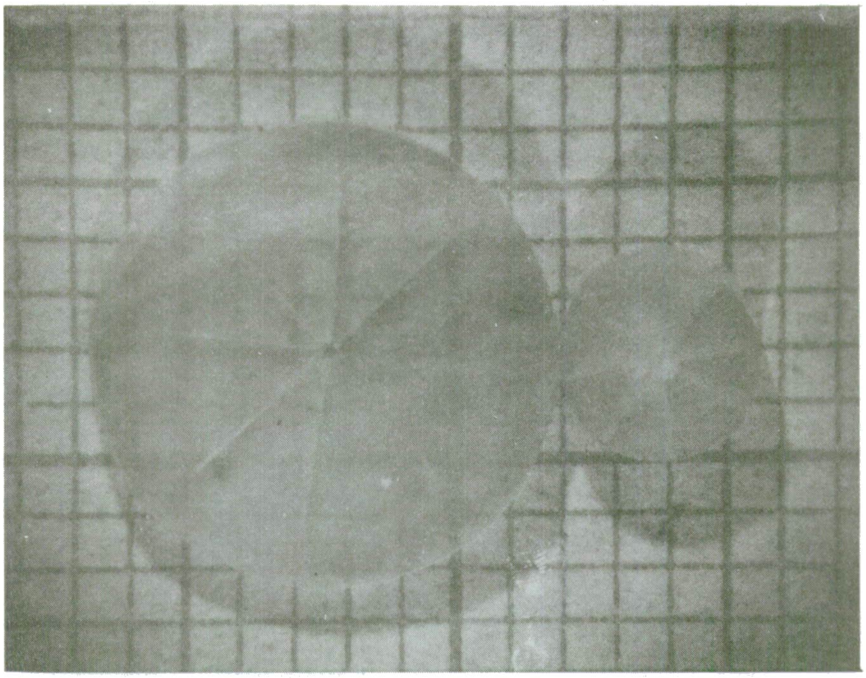

Figure 7. Sample 6b; Unburned, Burned, End View.

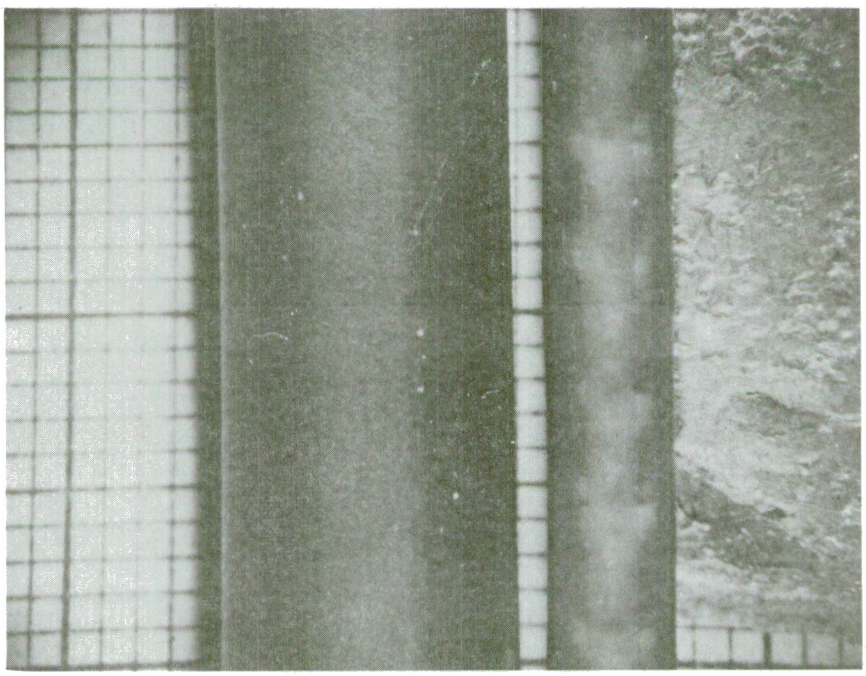

Figure 8. Sample 6b; Unburned, Burned, Side View.

As can be seen in Figure 5, the slits in sample 6a are wider, giving a larger free volume. This is not desirable from a ballistic standpoint as it will lower the chamber loading density. However, the added space may avoid the problem with re-sealing of the slits as the propellant burns from the outside in. Tests confirmed this, as the propellant broke up into pie-shaped segments. The results can be seen in Figure 9. These experiments were also used to pre-screen the samples for use in the closed bomb firings since the results from the interrupted burner studies were unambiguous. A simple visual inspection, with no additional data reduction, was sufficient to check for programmed splitting of the three samples. As a matter of fact, pressure-time histories of the interrupted burner experiments were useful in the interpretation of the results. In cases where no segmenting occurred, these curves were very smooth. When segmenting did occur, an abrupt change in pressure was observed. An example of this is indicated at "S" in Figure 10. Similarly, early rapid pressure rises were observed when the ends of the grains burned through prematurely.

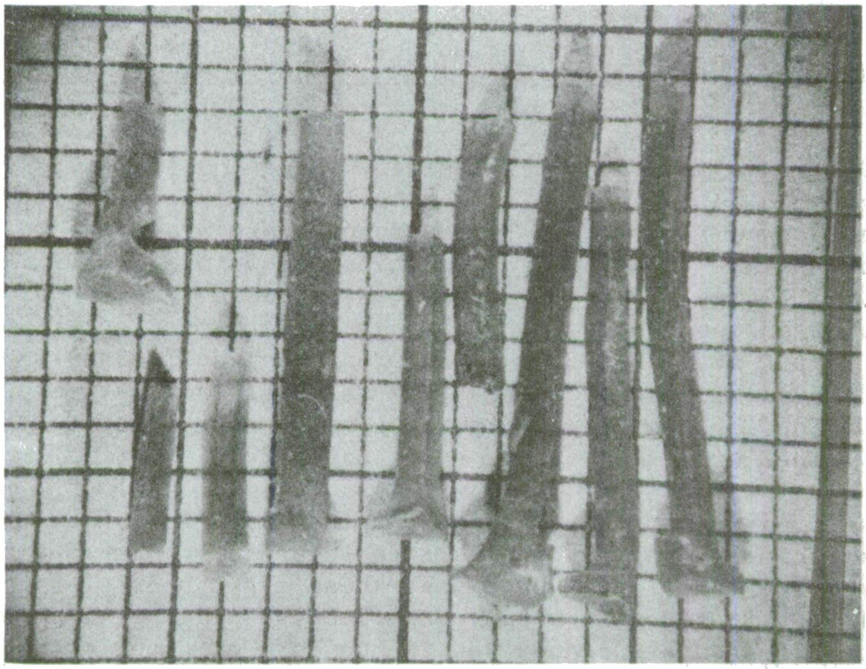

Figure 9. Sample 6a; Pie-Shaped Fragments.

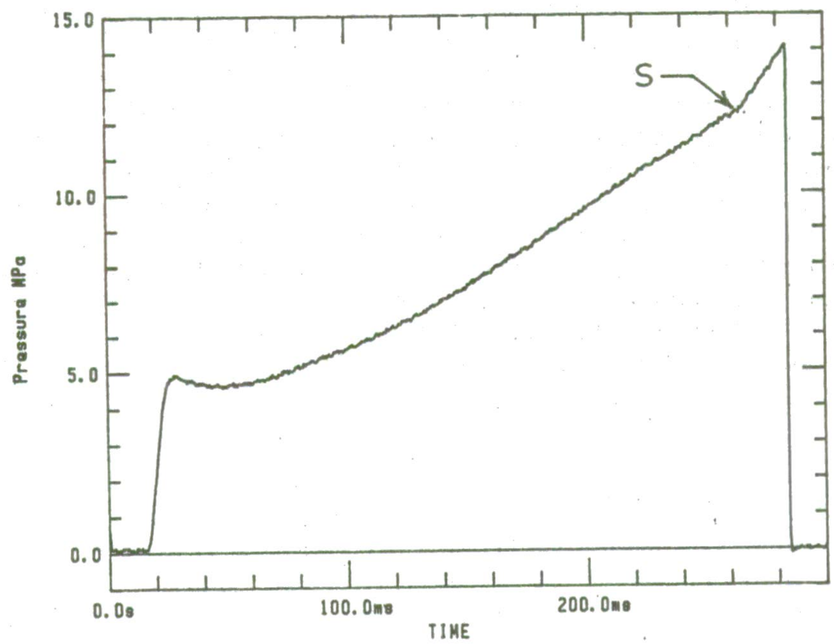

Figure 10. Pressure Time History for Segmented Burning

b. Closed bomb tests. Preliminary screening indicated that the best programmed splitting grains to use in the closed bomb testing would be sample 6a (see Figure 5). Two approaches are available to reduce the closed bomb data. The standard reduction, assuming a cord-like form function, will give "apparent burning rates" as a function of pressure. This is only an apparent burning rate as a programmed splitting form function is not available in the CBRED2 code. The inverse reduction will give normalized surface area (the ratio of the surface area at any instant divided by the original surface area) as a function of mass fraction burned with the burning rate as a given.

Past experience[8] has shown that information from the standard reduction technique may be difficult to interpret. Some standard reductions were done in the hope that these might be easier to interpret than similar reductions from past experiments. Figure 11 shows comparisons of standard reductions in the form of superimposed apparent burning rate curves for unsealed, or virgin grains, as well as grains sealed with estane 5712, Duco cement, epoxy, and a combination of acetone with Duco cement. As this form of data reduction did prove to be difficult to interpret, primarily because of the lack of a suitable form function, the rest of this discussion will revolve around the inverse reductions.

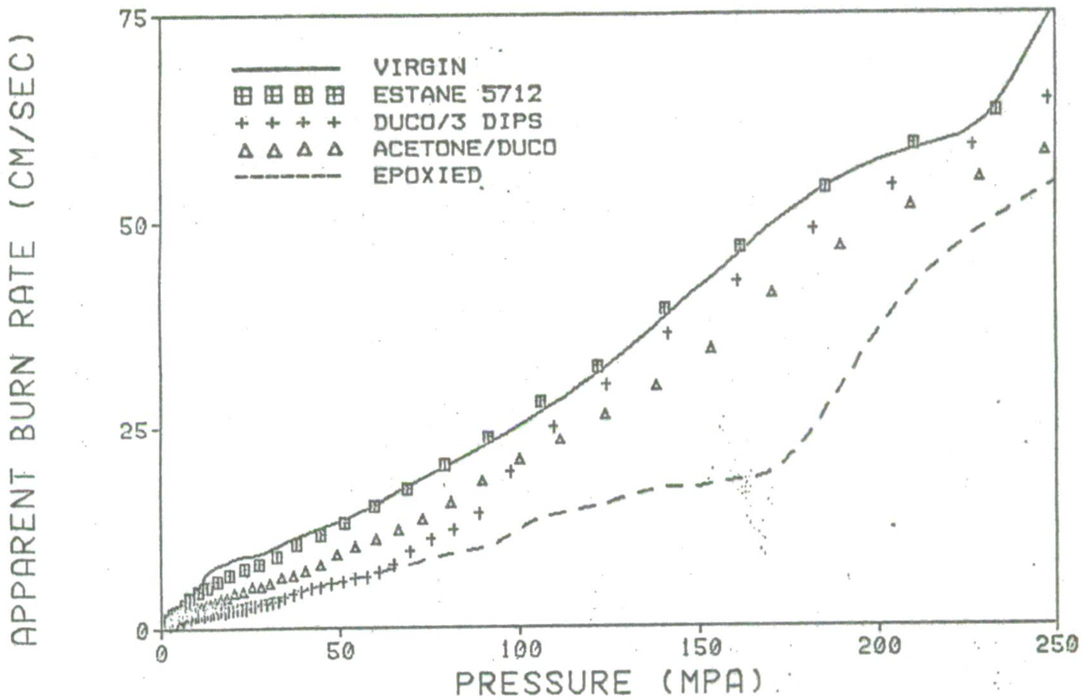

Figure 11. Superimposed "Apparent Burning Rate" Plots of Programmed Splitting Stick Propellant using Various End Sealing Techniques.

Inverse reductions are compared to each other in Figure 12. The input burning rates were derived from closed bomb firings of single perforated grains of this propellant, NOSOL 363. As can be observed, some of the experimental data showed an early increase in surface area. The results show that although some of the end sealing techniques worked to varying degrees, these sealing techniques were not reproducible. It was suspected that the premature surface area increase was due solely to inadequate end sealing techniques.

At this point questions were raised about the accuracy of the inverse reduction technique. These arose primarily in response to the abnormally high surface area ratios (as high as four, see Figure 12) that were derived using the CBRED2 code. Theoretically, the normalized surface area should have had a maximum value of 2.6 for the webs quoted. This value will vary with the grain dimensions. In our experiments, the abnormally high peaks that have occurred on the surface area profiles are found in the lower ten percent of the pressure versus time data. These data have typically been deemed as unreliable due to ignition start-up, flame spreading, and associated oscillations[11] and consequently were ignored.

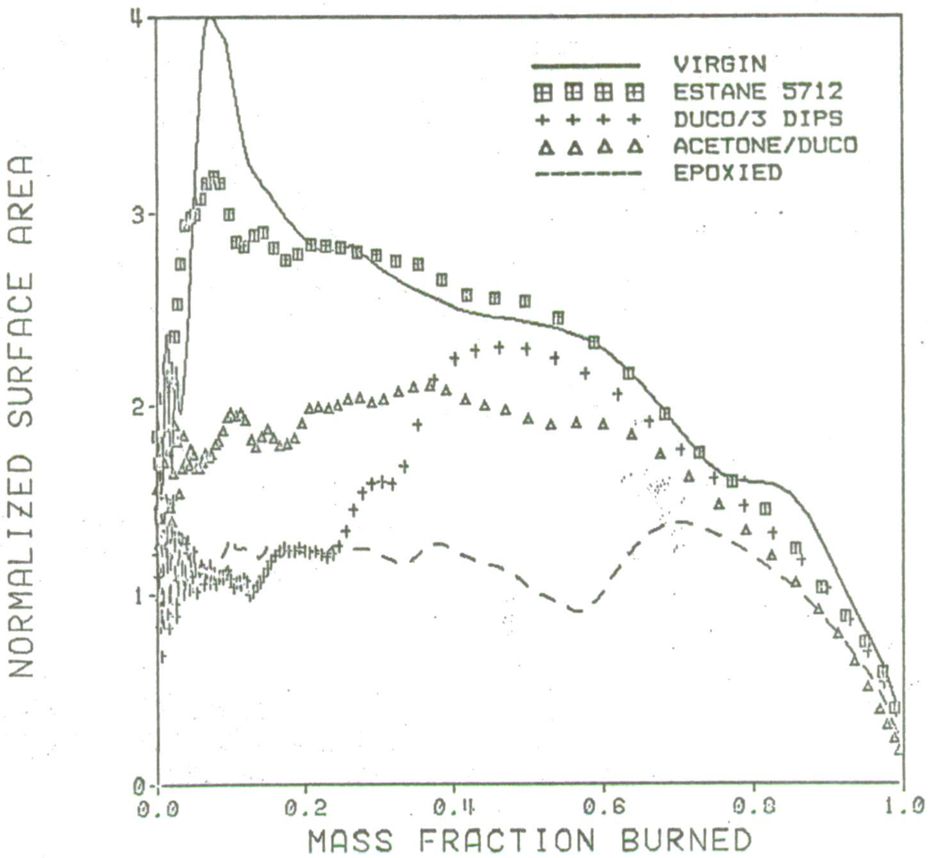

Figure 12. Superimposed Surface Area Profiles of Programmed Splitting Stick Propellant using Various End Sealing Techniques.

The data reduction code, CBRED2, can be made to accept pressure vs. time data from the keyboard. One of the interior ballistic codes, IBHVG2,[12] with a programmed splitting form function incorporated into it, was used to simulate a closed chamber experiment and generate a pressure vs. time data set. This data was used as input to the CBRED2 code as a means to validate the accuracy of the inverse reduction process. A comparison plot of two output data sets from the same input data is shown in Figure 13. The different plots come from the fact that the solid line, (A), was generated by the computer when a five point bridge length was used for differentiation whereas the dotted line, (B), was generated using a fifteen point bridge length for differentiation of the pressure vs. time curve.[8] As can be seen, the normalized surface area curves have maximum values of 2.0 or 2.4, depending on the differentiation bridge length. While this is not as high as the theoretical maximum of 2.6, the inverse reduction seems to be a reasonable guide as to what is actually happening in the closed vessel. This figure also shows that even the method of data reduction (i.e. the smoothing and differentiation bridge lengths) can impact the results. In order for any valid comparisons to be made, all of the reduction parameters must be equal.

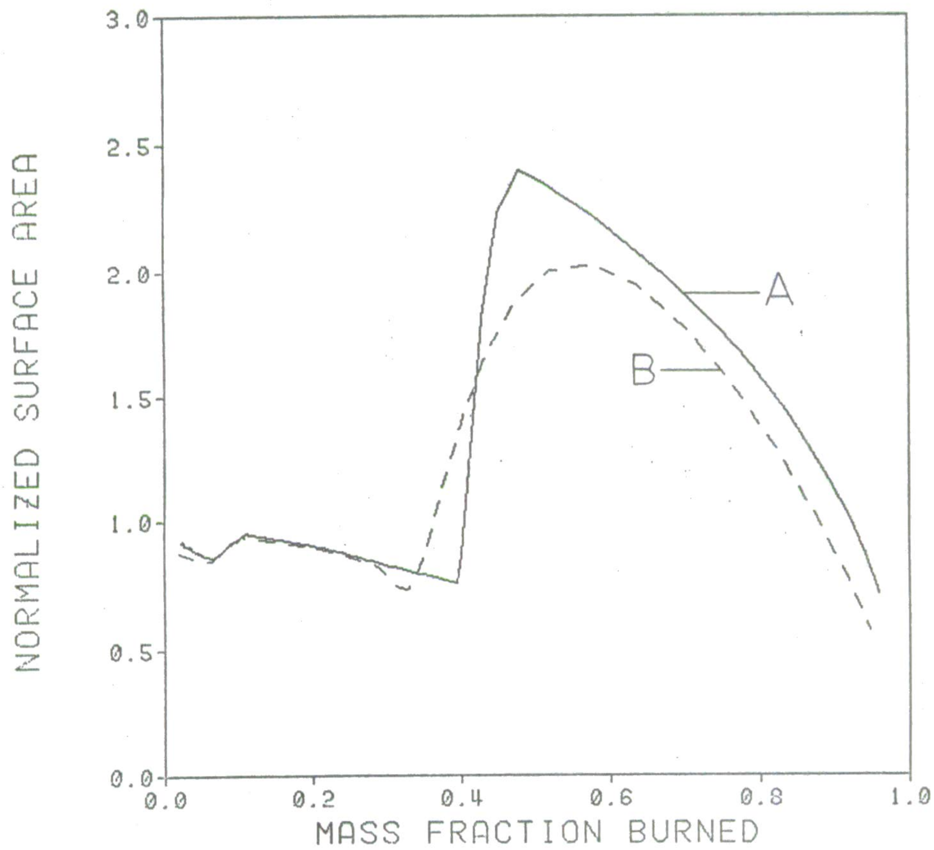

Figure 13. <u>Superimposed Inverse Reductions of Synthetic Pressure vs. Time Data.</u>
* "A" - no smoothing done and a five point bridge.
"B" - one smoothing pass and a fifteen point bridge.

The interior ballistic code, IBHVG2, was used to generate additional pressure versus time data. The propellant parameters that were varied were the slot width and subsequently, the web. Inverse reductions of this synthetic data are compared in Figure 14. Curve "A" represents the charge of the previous paragraph that had nine grains of propellant with a web of 0.94 mm. Curve "B" represents a charge of three grains that had a web of 0.43 mm and six grains with a web of 0.94 mm. Curve "C" represents a charge of eight grains with a web of 0.43 mm and one grain with a web of 0.94 mm. Results were as expected. As the web decreased, the increase in the normalized surface area took place earlier, at a lower fraction burned. Such an early rise in the normalized surface area, if observed in experimental data, could be due to premature burn through of the outer web if the slots were not centered in the grain, or to one or more of the grains opening up due to inadequate end sealing techniques.

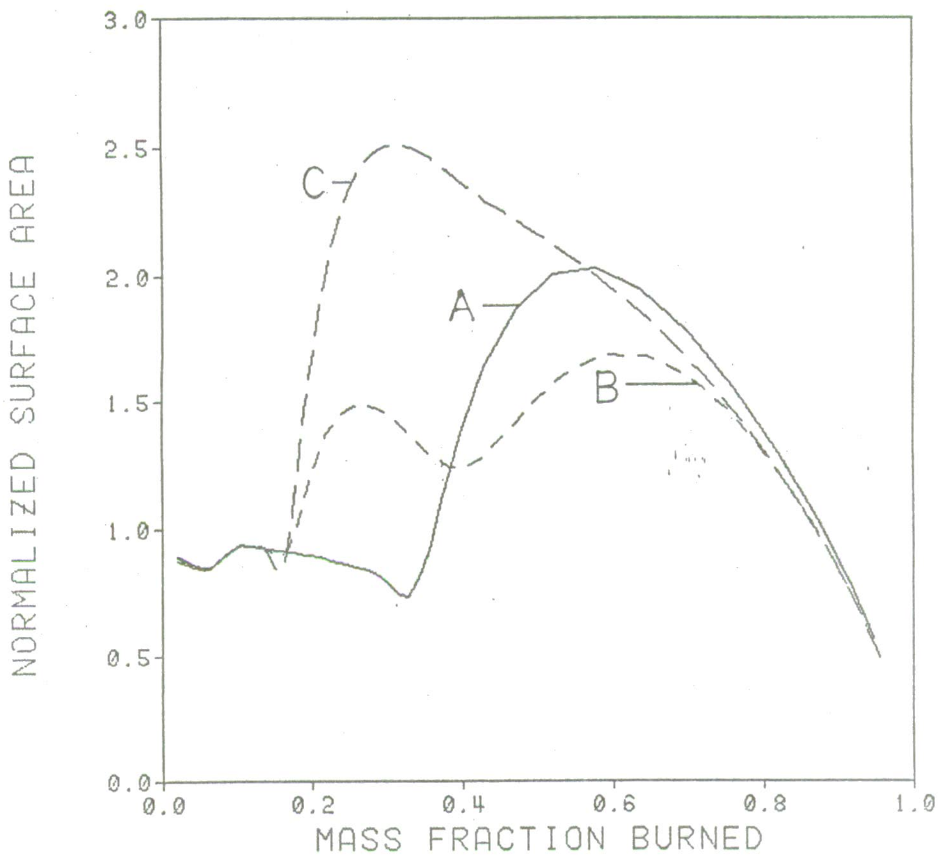

Figure 14. <u>Superimposed Inverse Reductions of Synthetic Pressure vs. Time Data.</u>

* "A" - nine grains with a web of 0.94 mm.
"B" - three grains with a web of 0.43 mm and six grains with a web of 0.94 mm.
"C" - eight grains with a web of 0.43 mm and one grain with a web of 0.94 mm.

Although the manufacturing differences between propellants 6a and 6b were rather small[10] they had a significant impact on the combustion process. We believe this had to do with the slot width characteristics of samples 6a and 6b. Such differences could cause ballistic variability from lot-to-lot and could even cause unpredictable ballistics when the firing temperature is changed. In effect, slivering may occur at different pressures depending on propellant temperature.

A very important aspect of the programmed splitting concept is the ability to seal the ends of the grain so that the flame does not propagate down the axis of the grain. This has turned out to be a difficult task. As was mentioned in the closed chamber section of this report, several techniques were used. Epoxy with aluminum disks proved to be very successful. An example can be seen in Figure 15. An unburned stick is at the bottom and a partially burned stick with aluminum end-caps is seen at the top. This sealing technique, however, is not practical for the gun environment. Other sealants were also used but with less success. The problem is that the flame can very easily penetrate into small orifices, and the end hole in the grain is very difficult to seal. Nevertheless, a minimum of three end coatings of Duco cement was a reasonable alternative to the epoxy-aluminum end cap. When three grains were burned in the interrupted burner, five out of the six ends remained sealed up to the blow-out pressure.

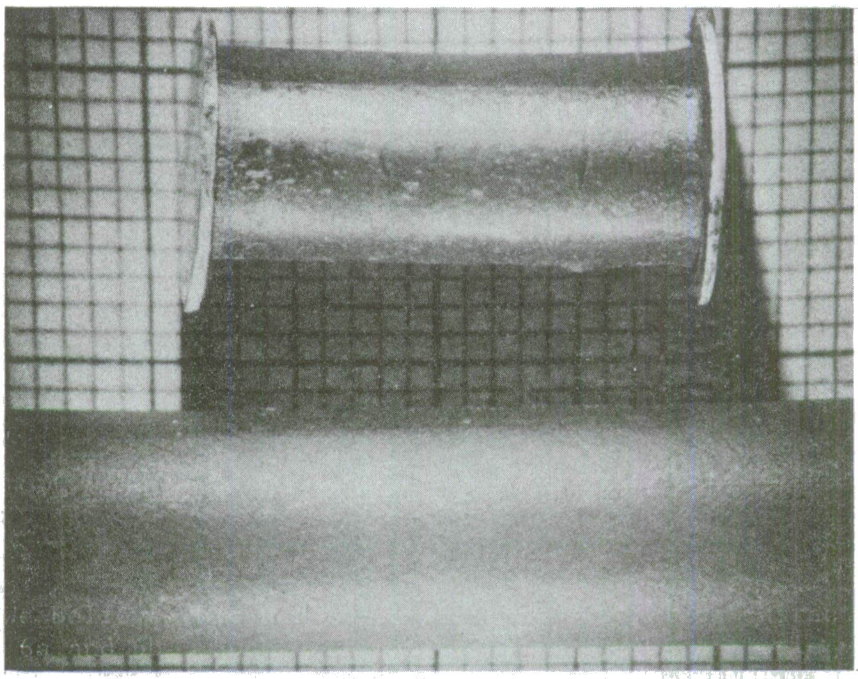

Figure 15. Sample 6b; Top - Burned with Aluminum End Caps Bottom - Unburned.

It is difficult to determine from closed chamber firings whether an increase in surface area is due to burning through the side wall of the grain or through the end sealant, except that the latter should result in non-reproducible results. Extinguished grains from the interrupted burner can help answer this question, as grains in which combustion has penetrated through the ends appear distinctly different from those that sliver properly.

2. FASTCORE:

a. Interrupted burner tests. There was some concern that the flame would propagate between the laminations of the fastcore propellant samples. If this happened the concept would be of no value ballistically as the programmed burning would not work. Interrupted burner firings of the laminated fastcore propellant showed good results as there was no evidence of delamination of properly made samples. To examine a worst case scenario, some samples were fired in which separations between layers were intentionally introduced. In these cases, the flame propagated between the layers as expected. Figure 16 shows a picture of an unburnt sample and two extinguished samples of fastcore propellant. In the well laminated sample, the propellant burned as programmed. In the other, where an intentional flaw was introduced, the flame penetrated between the layers resulting in a delamination of that sample.

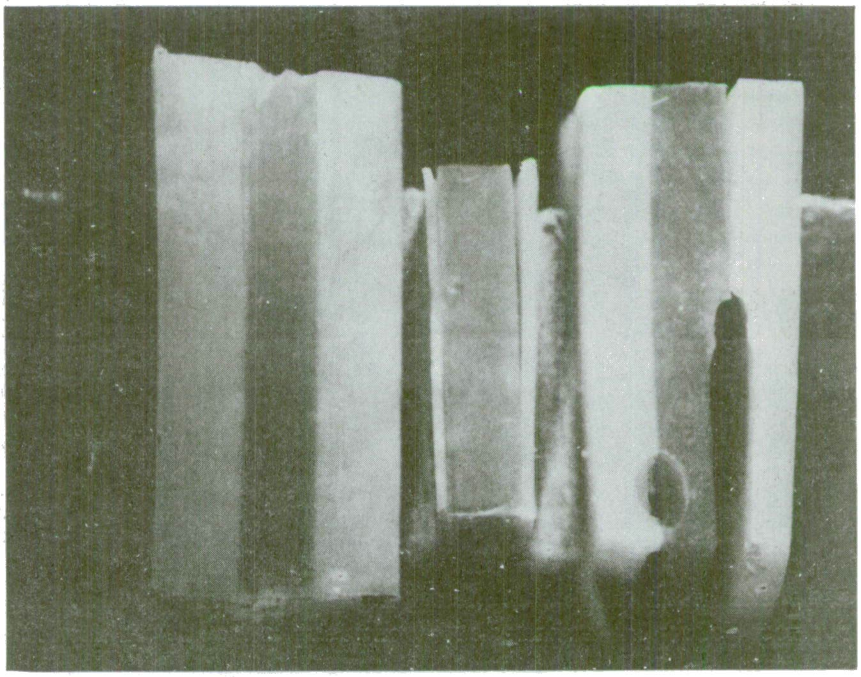

Figure 16. Fastcore: Unburned, Burned, Burned with Delamination.

b. Closed bomb tests. The fastcore propellant presented a different sort of problem for the closed bomb data reduction. The grains are composed of one third NOSOL 363 and two thirds NOSOL 318. The thermochemical input from either of the individual components would be inaccurate. The CBRED2 code permits the operator to input tabular values of thermochemical data. This variation is typically used to account for pressure effects on the thermochemistry. In this instance we used it to introduce thermochemical variations as a function of propellant mass fraction burned.

The fastcore propellant was expected to show an increase in the slope of the derived burning rate when the outer layer of NOSOL 318 burned through to the inner layer of NOSOL 363. This slope increase does present itself in the derived burning rates as can be seen in Figure 17. The slope break is not as pronounced as was expected. It is suspected that the gradual change may be due to the smoothing that takes place during data reduction, or to the method of thermochemical input, or possibly to an uneven burn through of the outer layer of the propellant grain.

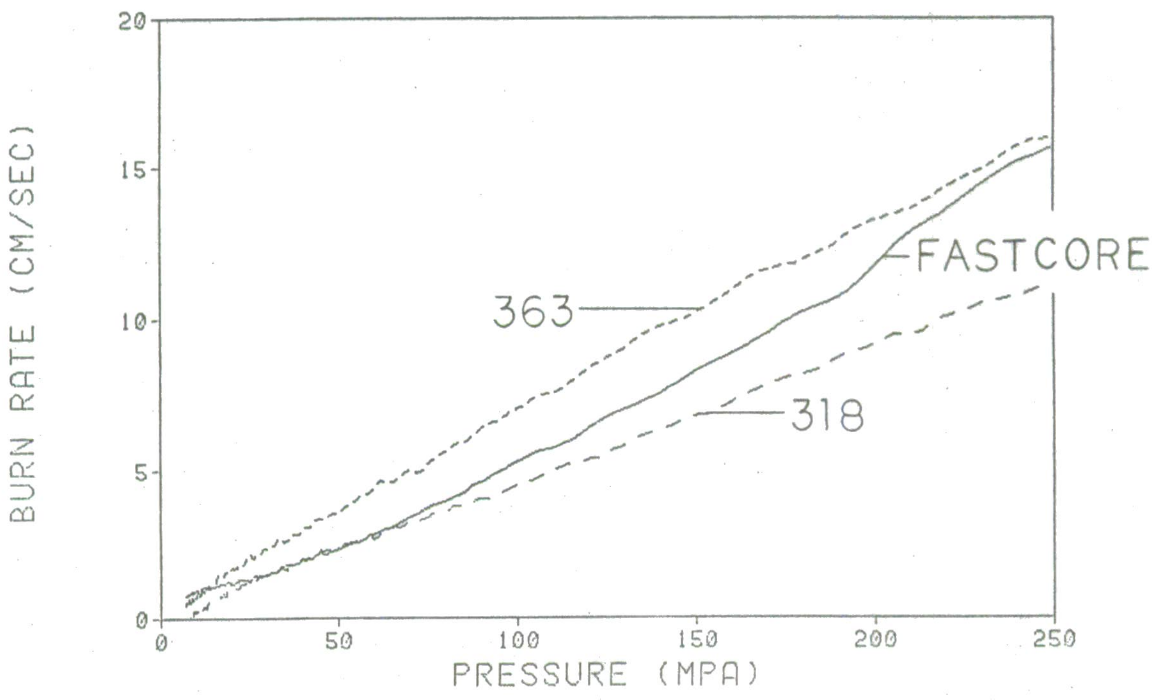

Figure 17. Burning Rate Curves for NOSOL 318, NOSOL 363, and Fastcore Propellant.

IV. CONCLUSIONS

Examples of the use of complementary experimental and data reduction techniques to characterize the combustion properties of innovative propellant samples have been presented. As a result, both of these grain concepts have demonstrated promise for future applications.

Small variations of the slotted perforation in the programmed splitting grains can affect if and when the grains will sliver. Too small of an internal slotted void can result in an annealing effect with no breaking up of the grains.

End sealing of the programmed splitting grains is still a problem, although the multiple dipping of the ends in Duco cement gave some good ballistic results.[10]

The integrity of the laminated bond of the fastcore propellant has been confirmed during firing. This is provided that there are no flaws in the grains.

Closed bomb testing has shown that it is possible to modify the gas generation rate through the use of the fastcore propellants.

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